Toward Seamless Weather-Climate Prediction with a Global Cloud Resolving Model

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LONG-TERM GOAL

The long-term goal of this project is to developing a seamless weather and climate prediction system that has capability to predict accurately both weather phenomena such as tropical cyclones (TC) and other extreme weather events and longer climate-scale phenomena such as the Madden-Julian Oscillation (MJO) and the El Nino-Southern Oscillation (ENSO). Organized moist convections in the tropical atmosphere have their origins at space scale of less than 10 km, and they play a key role in the initiation and maintenance of mesoscale weather events such as super cloud clusters and large-scale phenomena such as MJO. The Navy is in urgent need to develop such a global high resolution model that has a proper dynamic core and physics packages and is capable of representing realistically convection and clouds across a wide range of spatial and temporal scales and suitable for prediction of extreme events in regional and global scales.

OBJECTIVE

We aim to develop a new global model framework with the goal of reducing the uncertainty in moist convective processes. We propose to use the Geophysical Fluid Dynamics Laboratory (GFDL) High-Resolution Atmospheric Model (HiRAM) as a base framework for the next generation Navy global cloud resolving system. The HiRAM is based on a highly scalable finite volume dynamic core formulated on a cubed sphere. It is a non-hydrostatic, "cloud-resolving capable" global model designed to be applicable for a wide range of horizontal resolution from 100 km to 1 km. The objective of this project is to systematically evaluate the model's performance in weather (short and extended range)

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and climate (seasonal) predictions and provide a basis for the construction of next-generation Navy global cloud-resolving atmospheric forecast system suitable for operational requirements. We will in particular demonstrate the capability of this model in reproducing both short-range weather events such as mid-latitude synoptic systems and TCs and long-range climate variability such as MJO and ENSO teleconnection.

APPROACH

We plan to conduct the following three sets of experiments using HiRAM:

Weather forecast experiment. The first experiment is daily 10-day forecasts at the 25-km for a continuous period of one years, starting from spring of 2012. The 12.5-km resolution can be done for shorter period (for example, at hurricane season) pending on the availability of computing resources at GFDL. This experiment is designed to evaluate the model performance in the conventional "weather forecast mode". A systematic evaluation of the model short-range weather forecast capability will be conducted and results will be compared with current operational models such as the Navy NOGAPS/NAVGEM and NCEP GFS. A special attention will be to the forecast skill of TC track and intensity and winter mid-latitude synoptic-scale systems.

AMIP-type experiment. The second is an AMIP-type experiment. The model is run for 20 years (1990-2010) with monthly or weekly observed SST as a lower boundary condition. The inclusion of a longer period is needed in order to examine the model's performance in reproducing the atmospheric internal modes such as MJO and teleconnection patterns associated with El Nino. This experiment may be identified as a "free run mode". A 25 km or a 12.5 km resolution will be used for the AMIP run. The capability of reproducing the observed MJO and ENSO variability in the "free run mode" is crucial for extended-range weather forecast. It has been shown that TC and other synoptic wave activity are to a large extent controlled by low-frequency oscillations such as MJO and ENSO (Liebermann et al. 1994, Sobel and Maloney 2000, Fu et al. 2007, Hsu and Li 2011). Only when a model can capture realistic MJO structure and evolution in a free run, can this model predict the growth, propagation and phase transition of a real-case MJO event (otherwise the initial MJO signals would damp quickly with time).

Seasonal prediction experiment. The third is a seasonal prediction experiment similar to our TC forecast experiment. This may be termed as a "seasonal prediction mode". Such type of experiment is one step further toward achieving the goal of seamless weather-climate forecast. Through the evaluation of the model's seasonal forecast skill with forecasted SST (in which SST is determined based on the climatologic annual cycle plus a SST anomaly frozen at forecast initialization date), we will examine the model's practical predictability in extended range weather and seasonal climate prediction. The model's systematic bias in reproducing the seasonal mean state will be first examined, followed by the bias analysis in seasonal anomalies. The signal to noise ratio will be examined through multi-ensemble experiments. In addition to examining seasonal TC forecast skills in various basins, we will also examine the forecast skills in regional climate systems including the Asian monsoon, mid-latitude storm track, and the Pacific-North America pattern. The seasonal forecast experiments will be carried out for each season, in order to reveal the seasonal dependence of the model forecast capability.

Once the experiments are completed, we will further evaluate the model performance and assess the model forecast skills. Conventional diagnostic methods adopted at current operational centers will be used to evaluate the model short-range weather forecast capability. Other diagnosis matrices such as the Wheeler-Hendon RMM based anomaly correlation coefficient (ACC) index and the signal-noise ratio based predictability index will be used to assess the model extended-range forecast skill. A box difference index (BDI) will be applied to evaluate the relationships between TC genesis and large-scale pattern in various basins (e.g., tropical North Atlantic, eastern North Pacific, and western North Pacific). Additionally we will evaluate the model's performance in reproducing the MJO variability and the ENSO teleconnection patterns.

WORK COMPLETED

We aim to systematically evaluate the GFDL High-Resolution Atmospheric Model (HiRAM) capability in capturing both high-impact weather (such as TC) events and low-frequency (MJO and ENSO) climate oscillations. A long-term (1979-2008) AMIP type simulation with the prescribed observed SST field has been completed. In this year, we focused on the diagnosis of the model performance in capturing MJO and ENSO-like variability in the tropics and mid-latitudes.

RESULTS

1. MJO and ENSO teleconnection patterns as revealed from HiRAM AMIP simulations

Figure 1 shows observed and simulated MJO spectrum along the equator. It is clear that the model is able to capture, to a large extent, the observed spectrums of MJO, convectively coupled Kelvin waves, Rossby waves and inertial-gravity waves in northern winter.
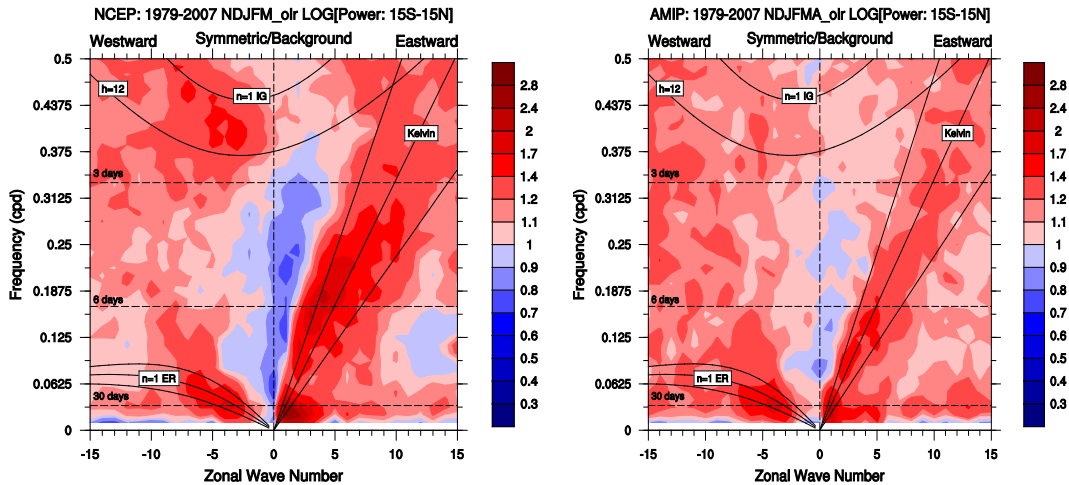

Fig. 1 Zonal wavenumber – frequency maps of power spectrum of observed (left) and simulated (left) intraseasonal (20-80-day) OLR fields averaged between 15S and 15N in northern winter (NDJFM)

The MJO in the winter exhibits a pronounced eastward propagation along the equator (left panel of Fig. 2). Such a propagation characteristic is well captured by the HiRAM AMIP simulation (right panel of Fig. 2).
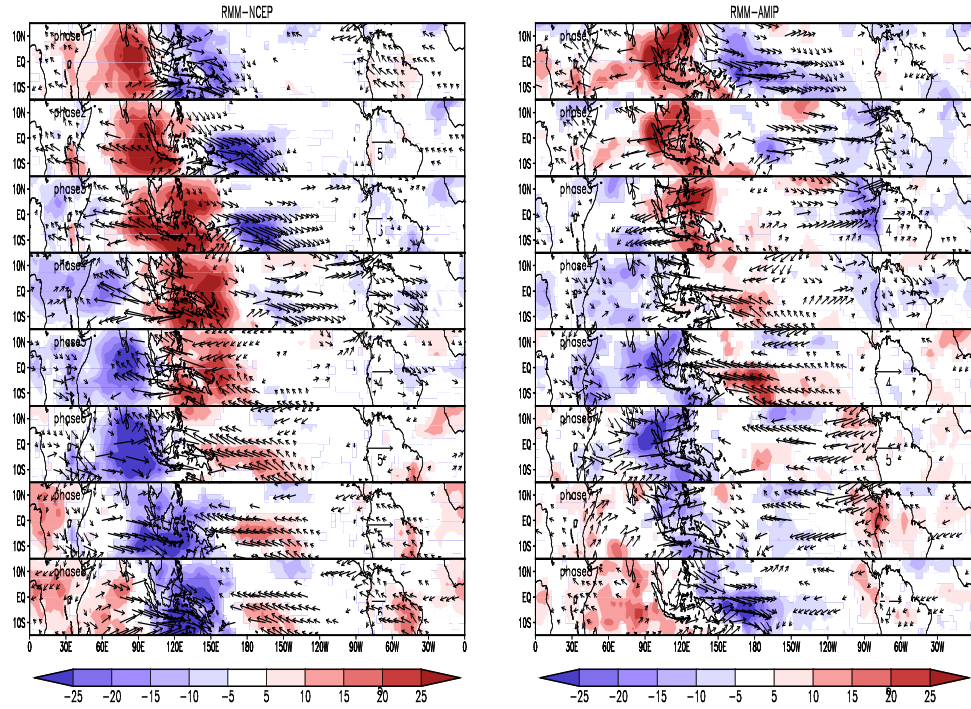

Fig. 2 RMM-based MJO phase-evolution maps in northern winter (left: observation, eight: simulation; shading: OLR, vector: 850hPa wind)

Different form northern winter, intraseasonal variability in boreal summer is dominated by northward propagation over the Asian monsoon region (such as Bay of Bengal and South China Sea). The top panel of Figure 3 shows the observed first two dominant EOF modes of rainfall structures associated with the boreal summer intraseasonal oscillation (ISO). While the maximum rainfall center in EOF1 is located in the equatorial eastern Indian Ocean, the dominant rainfall pattern in EOF2 exhibits a northwest-southeast tilted structure. Such rainfall patterns are well captured by the model.

In addition to the diagnosis of MJO variability, we also examined the model performance in capturing remote and local circulation patterns associated with central Pacific and eastern Pacific El Ninos. We noted that the teleconnection patterns over the Asian monsoon and tropical Indian Ocean are well reproduced for both types of El Ninos. However, for the Pacific-North America (PNA) pattern, the model can only reproduce it during the mature winter of the eastern Pacific El Nino, and cannot during the central Pacific El Nino.

Currently we are aiming to improve the model deep convective scheme, to better reproduce the MJO and ENSO patterns.
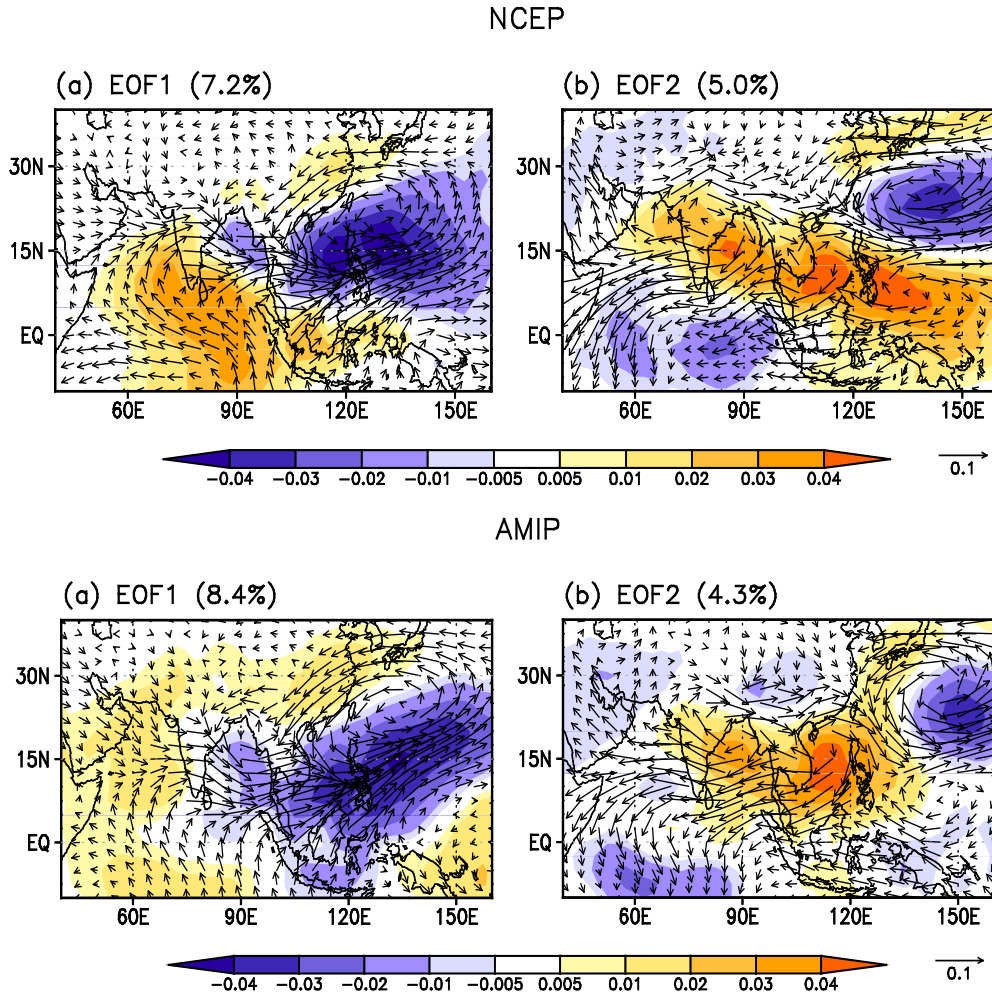
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Fig. 3 Observed (top panel) and simulated (bottom panel) first two EOF patterns of the intraseasonal (20-80-day) rainfall field in boreal summer (MJJAS) over the tropical Indian Ocean-western Pacific warm pool region

2. Changes of MJO features under global warming

This study estimates MJO change under the A1B greenhouse gas emission scenario using the ECHAM5 AGCM whose coupled version (ECHAM5/MPI-OM) has simulated best MJO variance among fourteen CGCMs. The model has a horizontal resolution at T319 (about 40 km) and is forced by the monthly evolving SST derived from the ECHAM5/MPI-OM at a lower resolution of T63 (about 200 km). Two runs are carried out covering the last 21 years of the 20th and 21st centuries. The NCEP/NCAR Reanalysis products and observed precipitation are used to validate the simulated MJO during the 20th century, based on which the 21st century MJO change is compared and predicted.

The validation indicates that the previously reported MJO variances in the T63 coupled version are reproduced by the 40-km ECHAM5. More aspects of MJO, such as the eastward propagation, structure, and dominant frequency and zonal wavenumber in power spectrum, are simulated

reasonably well. The magnitude in power, however, is still low so that the signal is marginally detectable and embedded in the over-reddened background.

Under the A1B scenario, the T63 ECHAM5/MPI-OM projected an over 3 K warmer tropical sea surface that forces the 40-km ECHAM to produce wetter tropics. The enhanced precipitation variance shows more spectral enhancement in background than in most wavebands. The zonal winds associated with MJO, however, are strengthened in the lower troposphere but weakened in the upper. On the one hand, the 850-hPa zonal wind has power nearly doubled in 30-60-day bands, demonstrating relatively clearer enhancement than the precipitation in MJO with the warming. A 1-tailed Student's t-test suggests that most of the MJO changes in variance and power spectra are statically significant. Subject to a 20-100-day band-pass filtering of that wind, an EOF analysis indicates that the two leading components in the 20th–century run have a close structure to but smaller percentage of explained-to-total variance than those in observations; the A1B warming slightly increases the explained percentage and alters the structure. An MJO index formed by the two leading principal components discloses nearly doubling in the number of prominent MJO events with a peak phase occurring in February and March. A composite MJO life cycle of these events favors the frictional moisture convergence mechanism in maintaining the MJO and the nonlinear wind-induced surface heat exchange (WISHE) mechanism also appears in the A1B warming case. On the other hand, the Slingo index based on the 300-hPa zonal wind discloses that the upper-level MJO tends to be suppressed by the A1B warming, although the loose relationship with ENSO remains unchanged. Possible cause for the different change of MJO in the lower and upper troposphere is discussed.

3. Projected future increase in Hawaiian tropical cyclones

Possible future changes in tropical cyclone (TC) activity around the Hawaiian Islands are investigated using the state-of-the-art climate models[1–3]. We find that the future experiments (2075–2099) project a consistent and robust increase in frequency of TC occurrence around the Hawaiian Islands by about 179% compared with the simulated present-day climate (1979–2003). We apply a statistical methodology[3] to address factors responsible for the increase in TC frequency. The results reveal that the TC track change is the major factor responsible for the increased TC frequency. This implies significant future changes in large-scale flows. We find that the large-scale westward steering flows indeed increased in the subtropical central to eastern Pacific, which acts as a "pathway" leading more TCs from farther eastern Pacific toward the Hawaiian Islands. The steering flow changes are robust regardless of models used and the assumed global warming scenarios. These results highlight possible future increase in storm-related socio-economic damage in the future in the Hawaiian Islands.

4. Changes to environmental parameters controlling TC genesis under global warming

This study uses the MRI high-resolution Atmospheric Climate Model to determine whether environmental parameters that control tropical cyclone (TC) genesis in the Western North Pacific (WNP) and North Atlantic (NA) may differ in the global warming state. A box difference index (BDI) was computed to quantitatively assess the role of environmental controlling parameters. The diagnosis of the model outputs shows that in the WNP, dynamical variables are of primary importance for separating developing and non-developing disturbances in the present-day climate, and such a relationship remains unchanged in a future warmer climate. This is in contrast to the NA, where BDI increases for all dynamic variables investigated while it shows little change for thermodynamic

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variables. This implies that, when compared with the present-day climate in which thermodynamic variables have a major control on TC genesis, dynamic and thermodynamic variables have equal control in the NA under the future warmer climate.

IMPACT/APPLICATIONS

The current effort may lead to the development of next generation navy operational weather-climate prediction model.

TRANSITIONS

Results from this study may lead to the development of a base model for next-generation navy operational seamless weather-climate forecast system. The model dynamic core and physics package may be transitioned into NRL as a 6.4 project.

RELATED PROJECTS

This project is complementary to our NSF funding entitled "Upscale feedback of tropical atmospheric synoptic-scale variability to intra-seasonal oscillation" in which we are investigating two-way interactions between the synoptic-scale motion (including TC) and MJO.

PUBLICATIONS

The following are papers published in 2013 that are fully or partially supported by this ONR grant:

Liu, P., T. Li, B. Wang, M. Zhang, J.-J. Luo, Y. Masumoto, X. Wang, and E. Roekner, 2013: MJO change with A1B global warming estimated by the 40-km ECHAM5. *Clim. Dyn.*, **41** (3-4), 1009-1023, doi:10.1007/s00382-012-1532-8.

Murakami, H., B. Wang, T. Li, and A. Kitoh, 2013: Projected future increase in tropical cyclones near Hawaii. *Nature Climate Change*, **3**, 749-754, doi:10.1038/nclimate1890.

Murakami, H., T. Li, and M. Peng, 2013: Changes to Environmental Parameters that Control Tropical Cyclone Genesis under Global Warming. *GRL*, **40** (10), 2265-2270, doi:10.1002/grl.50393.